NS102 Lecture 14

This is not the big bang!

News of the week

- No office hours on Thursday
- Lab this week: The Hubble constant
- Start reading Hawking
- Exam #2: May 20th
- Last lecture: Tuesday June 1st
- Final Exam: Tuesday, June 8th, 10:30am-12:30pm

Space is expanding

Edwin Hubble

1929

We are not the center of the expansion of the universe

Every galaxy sees the expansion

Cosmological Principle

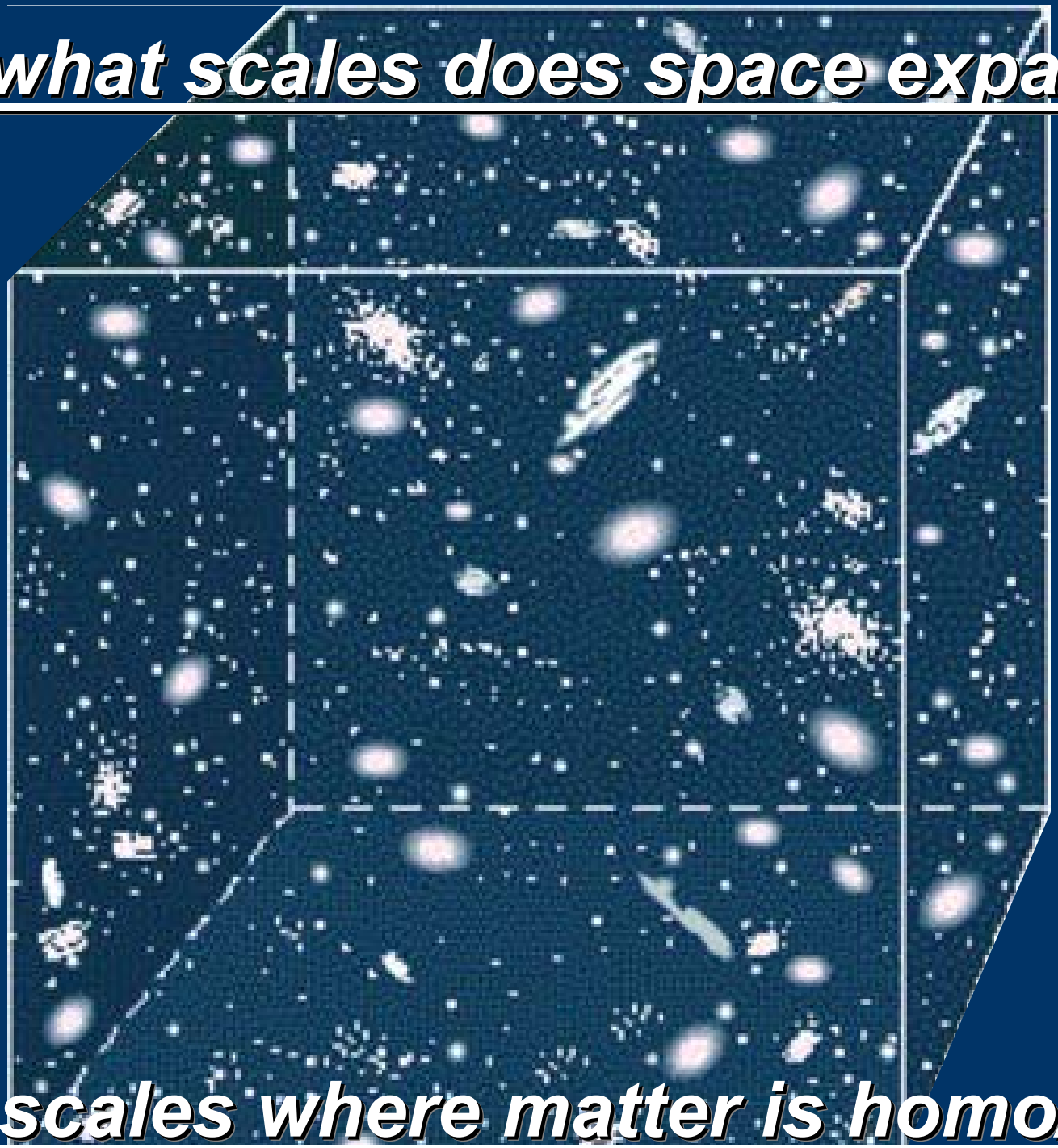
The universe (on large scales) is the same everywhere

- no special point in the universe (no center)
- no special set of points (no edge)

The universe (on large scales) is homogeneous & isotropic

- homogeneous: the same at every point
- isotropic: the same in every direction

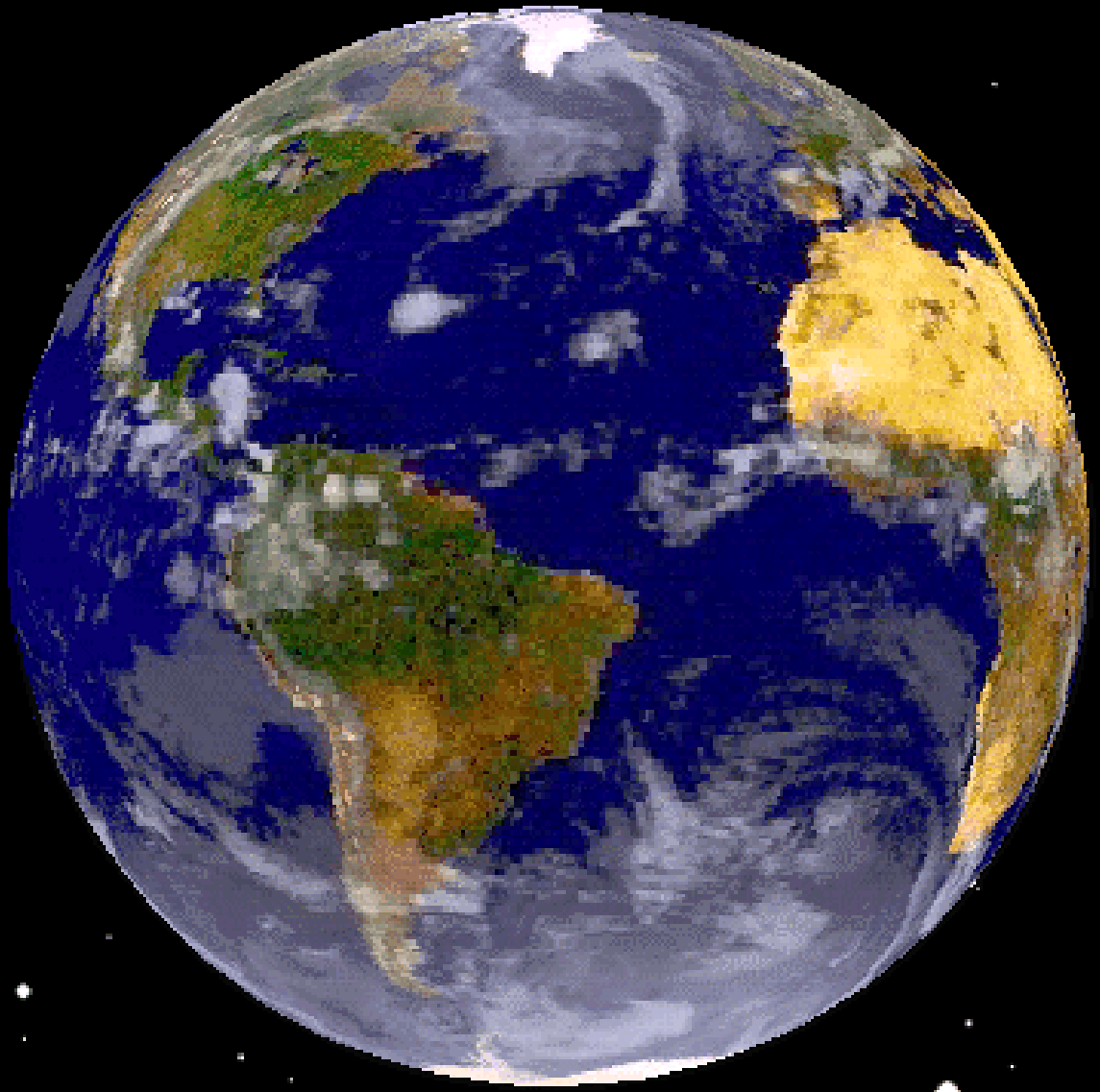
On what scales does space expand?



On scales where matter is homo/iso


No net gravitational force…
space experiences
“homogeneity & isotropy”

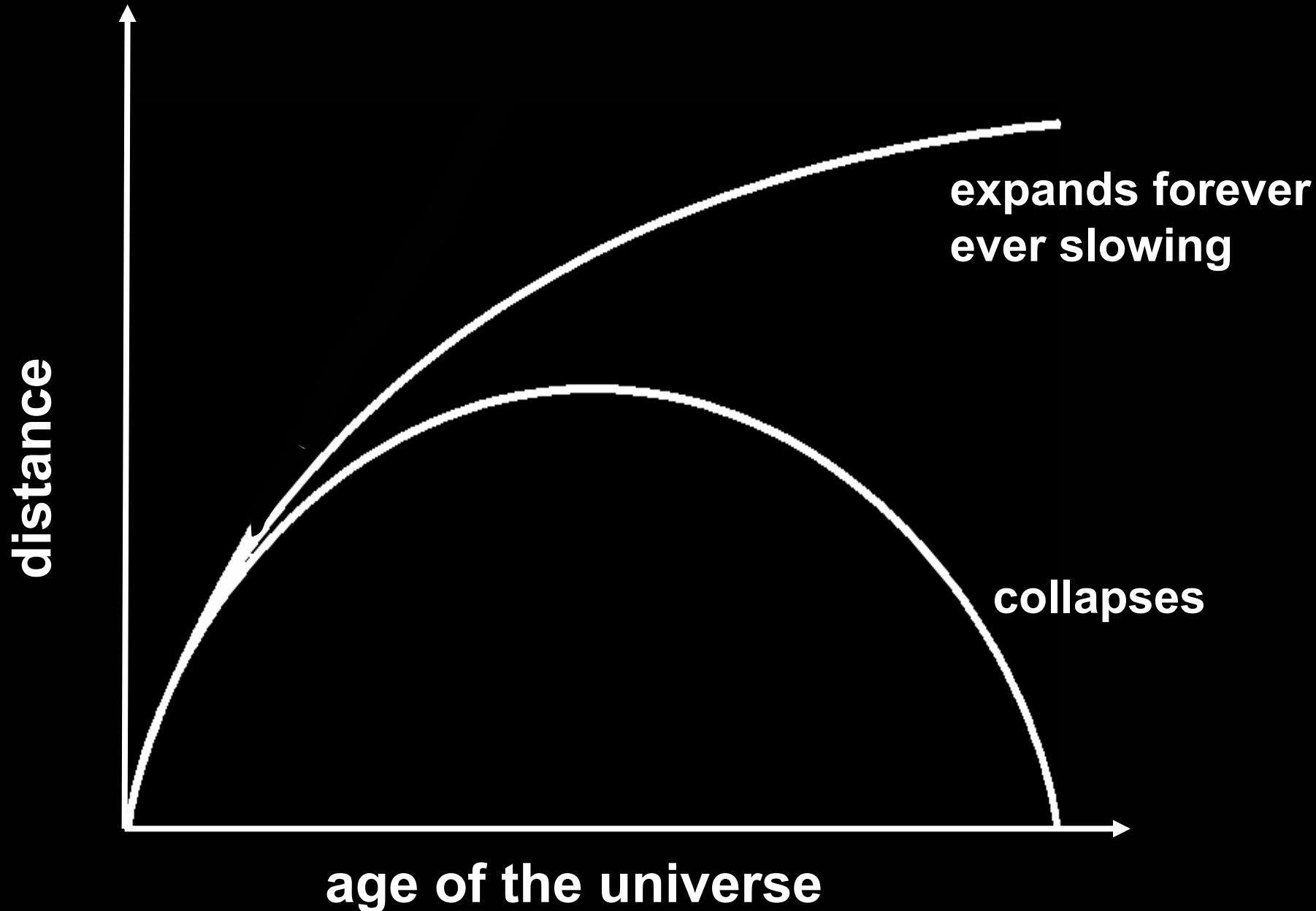
It ain't homo/iso around here!



Into what does space expand?

The big bang is an expansion of space

Gravity affects the expansion

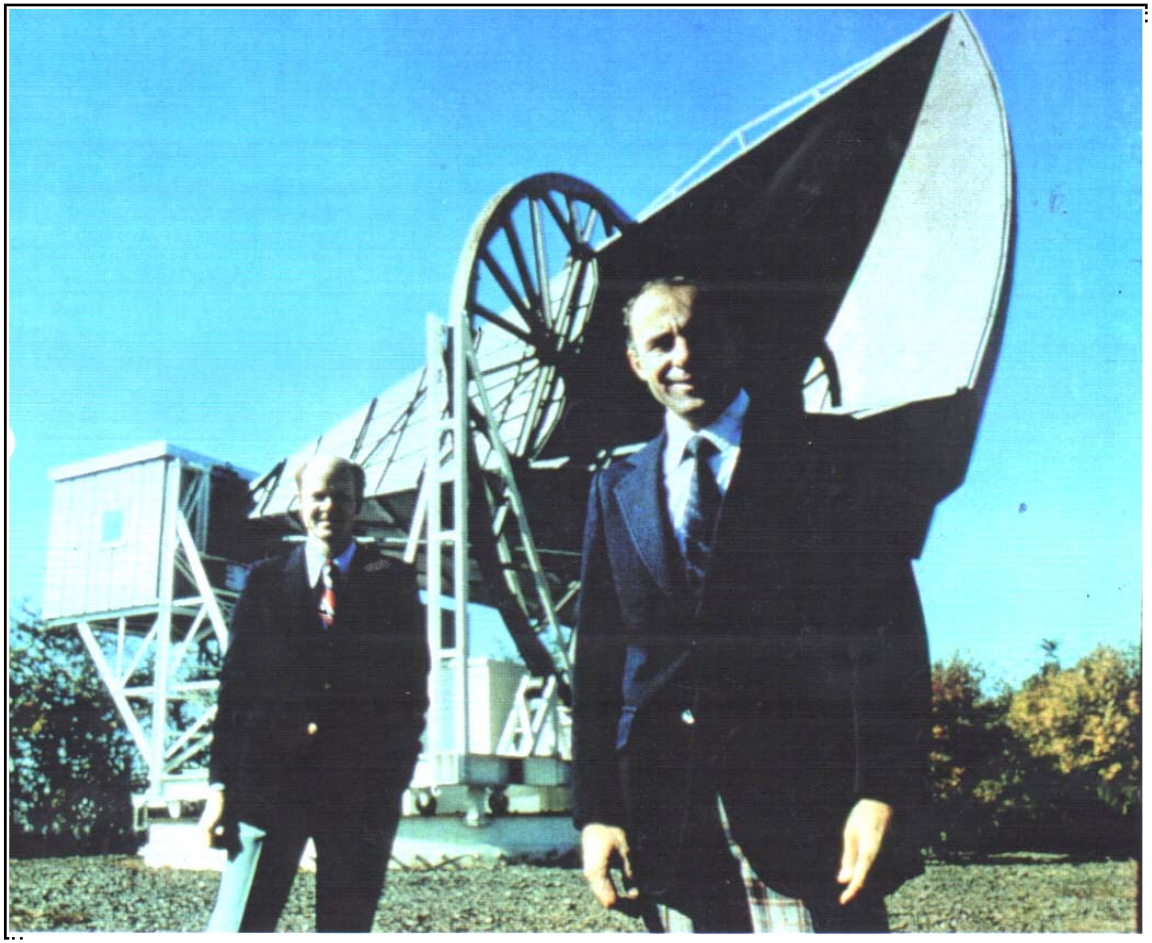


The universe is radiant

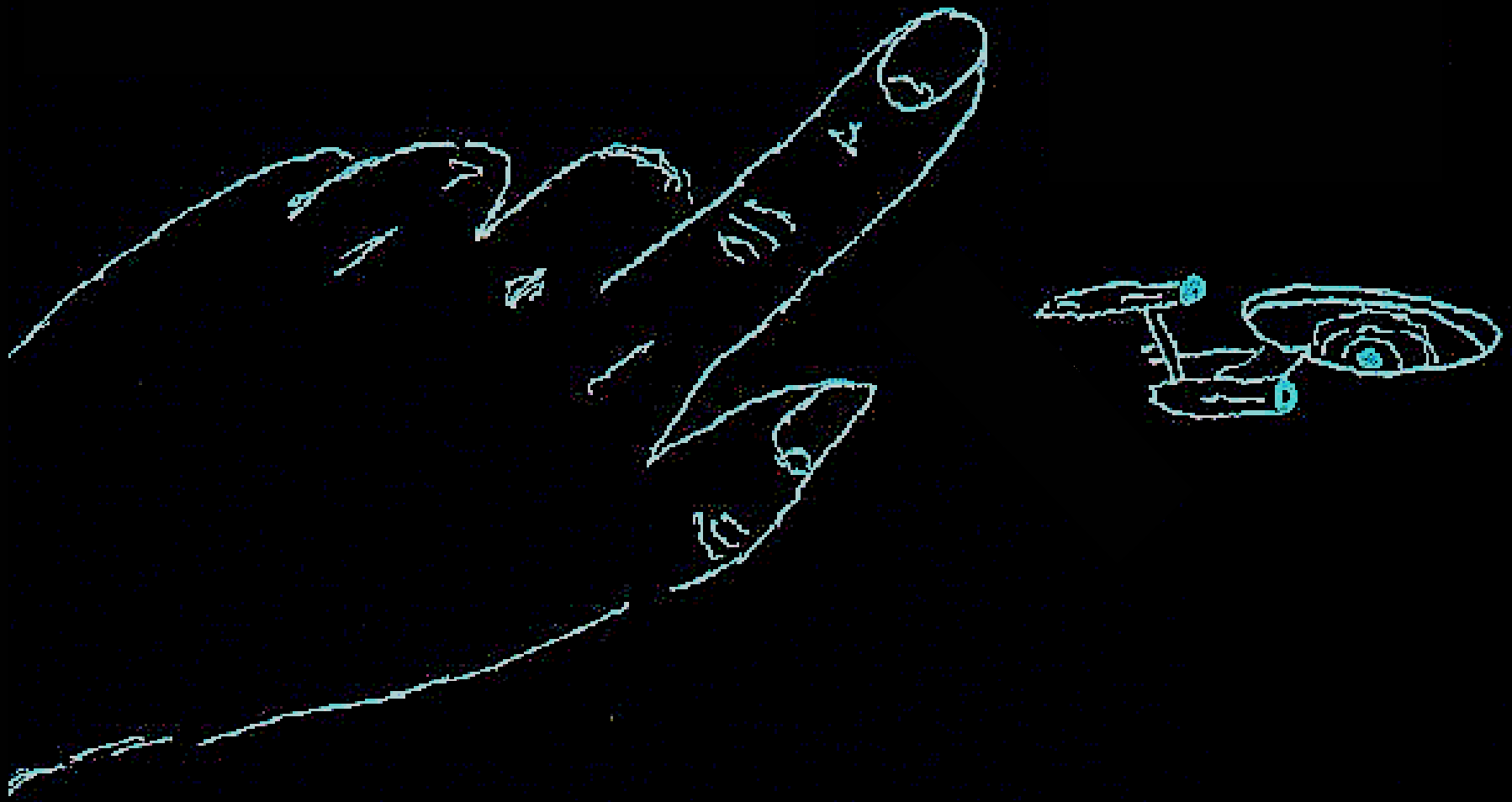
Arno Penzias

Robert Wilson

1965



Cosmic background radiation

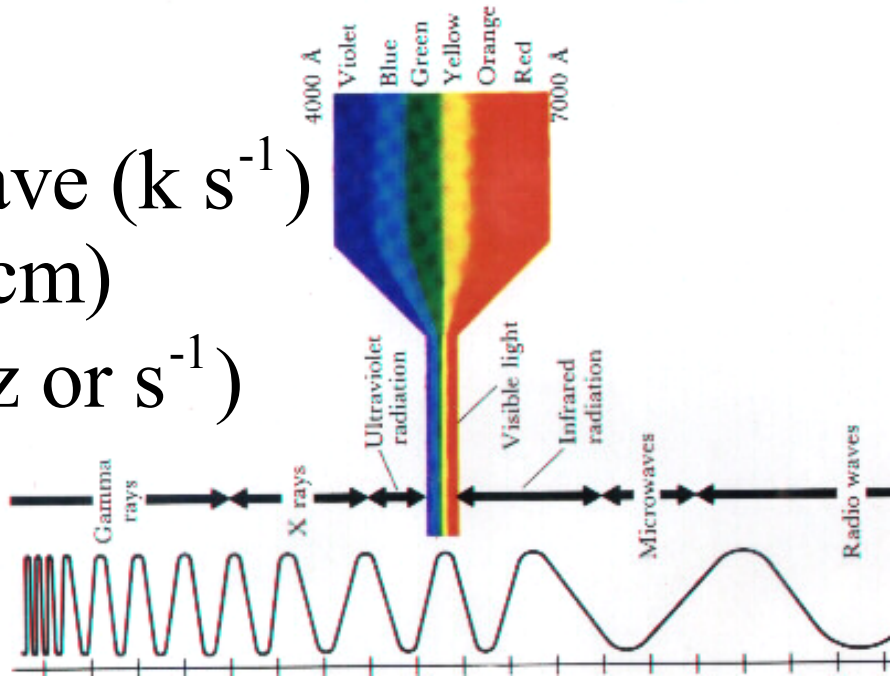


T = 3K = – 454° F

Facts about light

1. Light is a wave

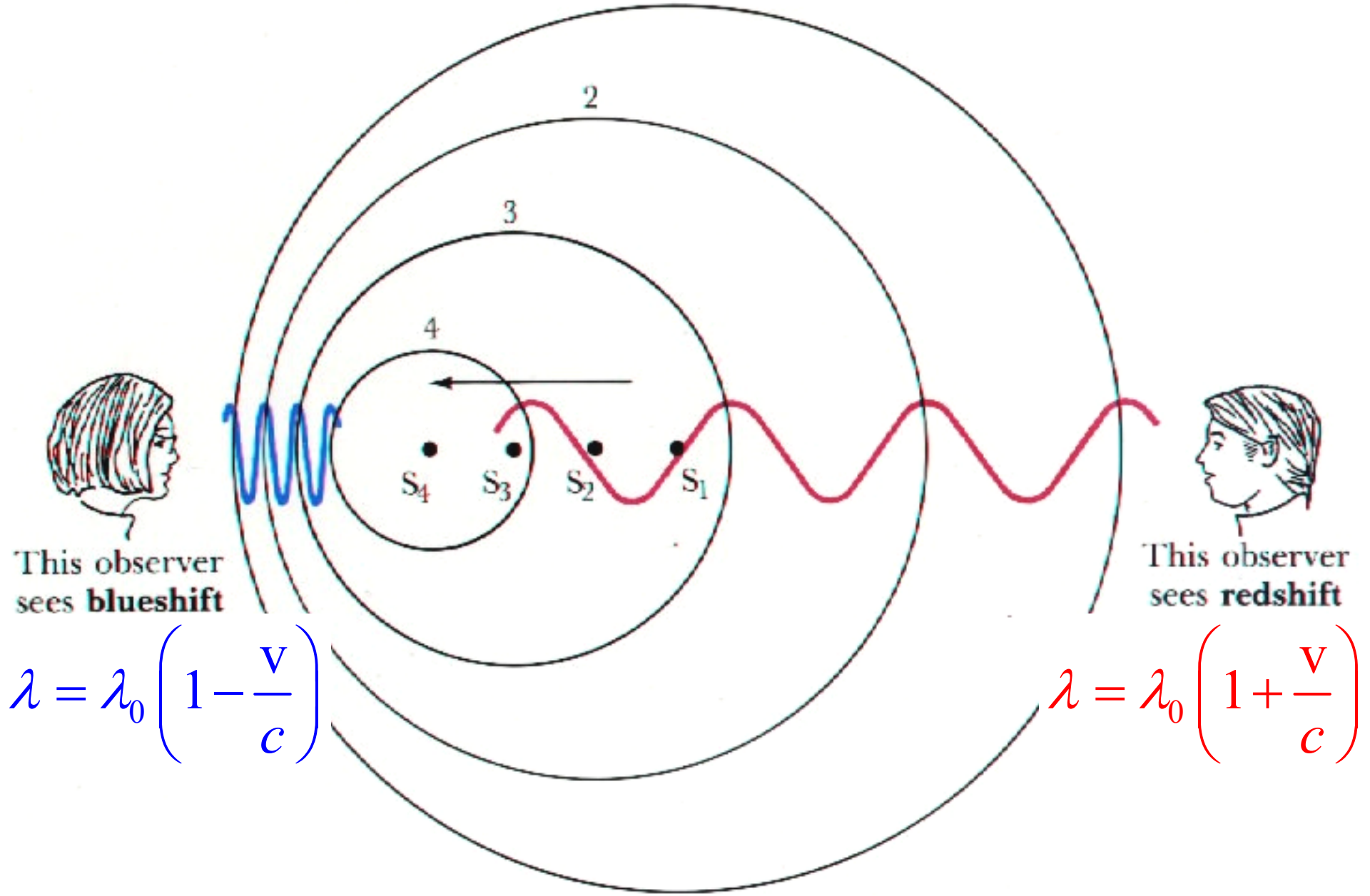
$$c = \lambda \nu \quad \begin{cases} c = \text{ velocity of wave (k s}^{-1}) \\ \lambda = \text{ wavelength (cm)} \\ \nu = \text{ frequency (Hz or s}^{-1}) \end{cases}$$



2. The wavelength is quantized

Visible Emission Spectrum

3. Doppler shift



$$\lambda = \lambda_0 \left(1 - \frac{v}{c}\right)$$

$$\lambda = \lambda_0 \left(1 + \frac{v}{c}\right)$$

3. Light is a particle

- **Particles of light are "photons"**
- **Photons have energy**

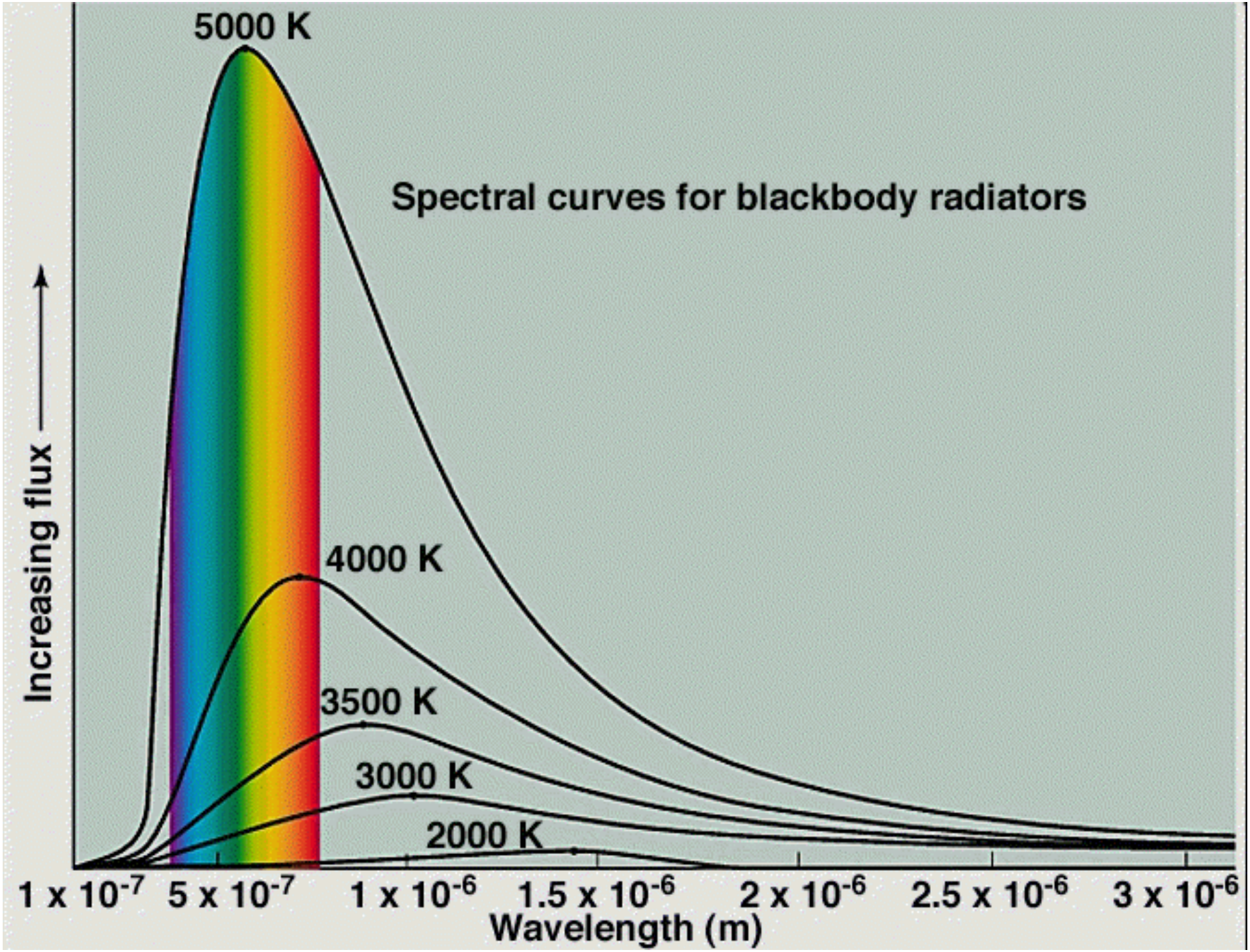
$$E_\gamma = h\nu = hc/\lambda \quad h = \text{Planck's constant}$$

(unit of the quantum)

- **Temperature is a measure of energy of the photons**

$$\left\langle E_\gamma \right\rangle = h\left\langle \nu \right\rangle = k_B T \quad k_B = \text{Boltzmann's constant}$$

$$\left\langle \cdots \right\rangle = \text{ average}$$


5000 K
Spectral curves for blackbody radiators
Increasing flux
4000 K
3500 K
3000 K
2000 K
1 x 10-7
5 x 10-7
1 x 10-6
1.5 x 10-6
2 x 10-6
2.5 x 10-6
3 x 10-6
Wavelength (m)

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$$\left\langle \cdots \right\rangle = \text{ average}$$

- **If wavelength stretched, E decreases, T decreases**

Energy of photons decrease

- Where does the energy go?
- What about conservation of energy?

Conservation of Energy?

Classical physics: $\dfrac{dE}{dt} = 0 \quad \Rightarrow \quad E = \text{constant}$

energy, momentum, mass

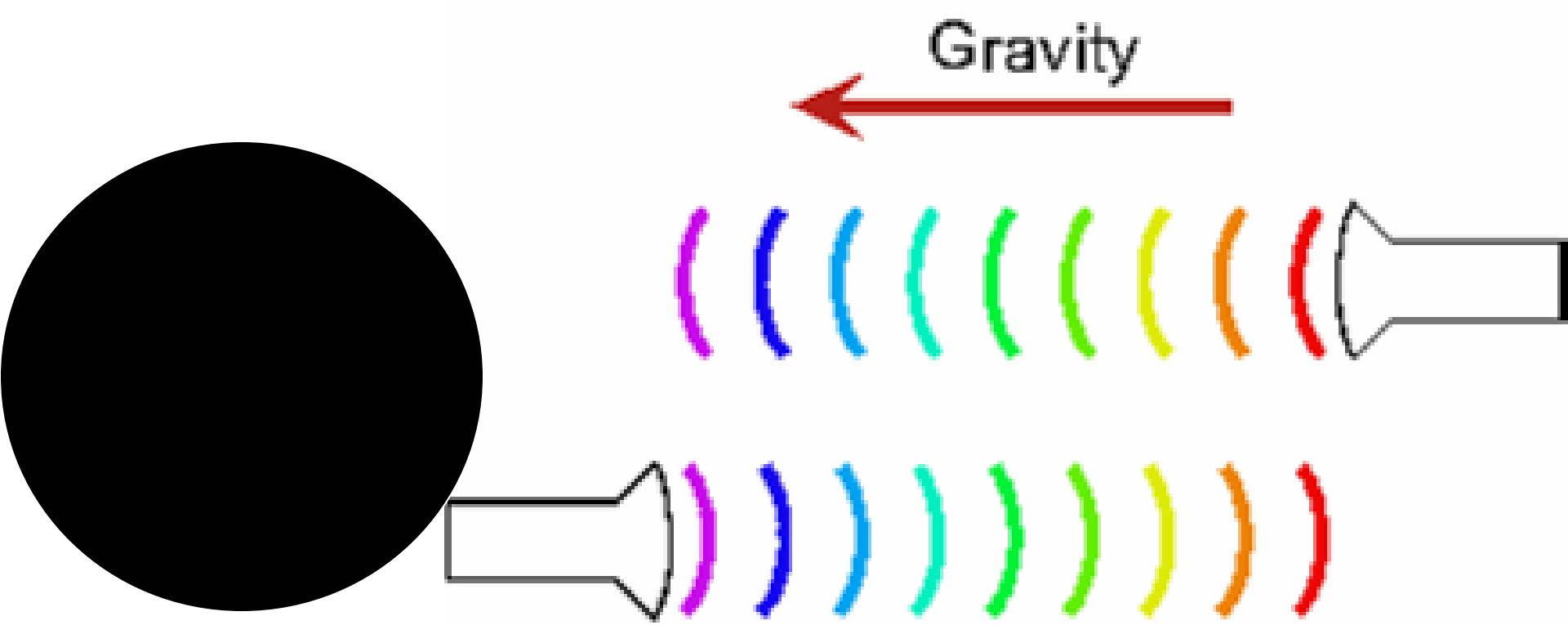
Special relativity:
($E = mc^2$ and all that) $\dfrac{dT^{\mu\nu}}{dx^{\mu}} = 0$

space and time

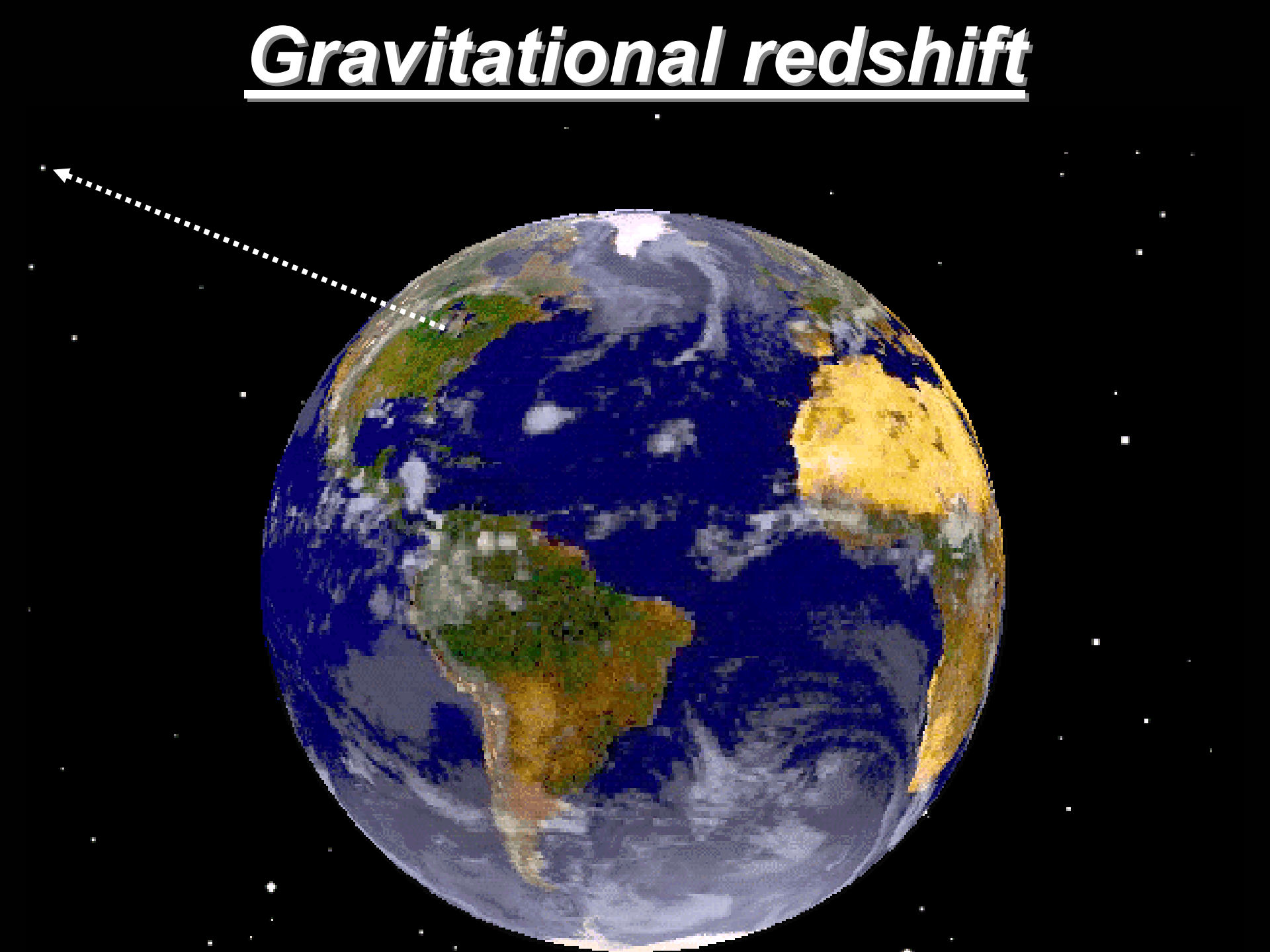
General relativity:
(gravity) $\dfrac{dT^{\mu\nu}}{dx^{\mu}} + \Gamma^{\mu}_{\mu\alpha} T^{\alpha\nu} + \Gamma^{\nu}_{\mu\alpha} T^{\mu\alpha} = 0$

gravity

Gravitational redshift

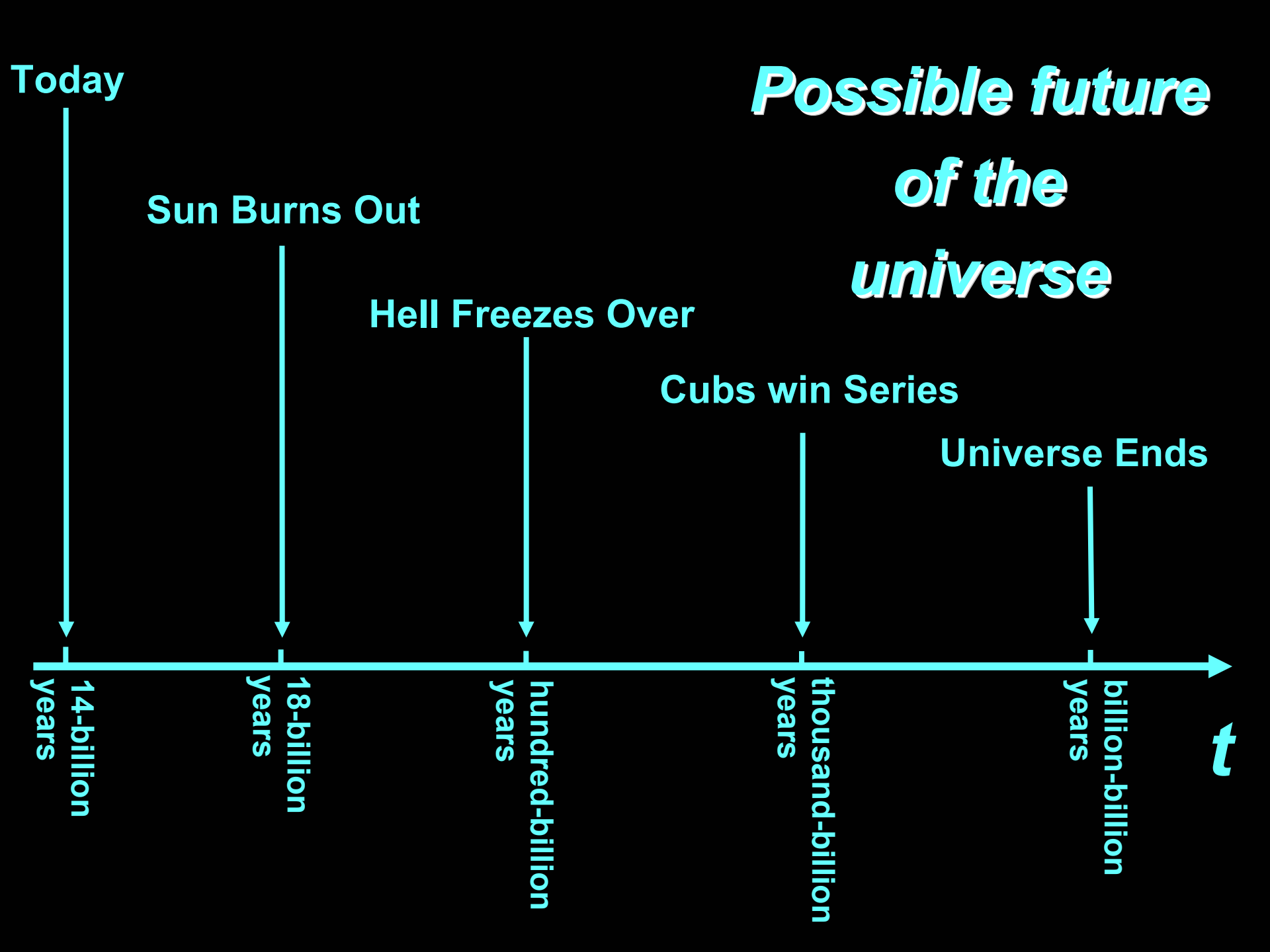


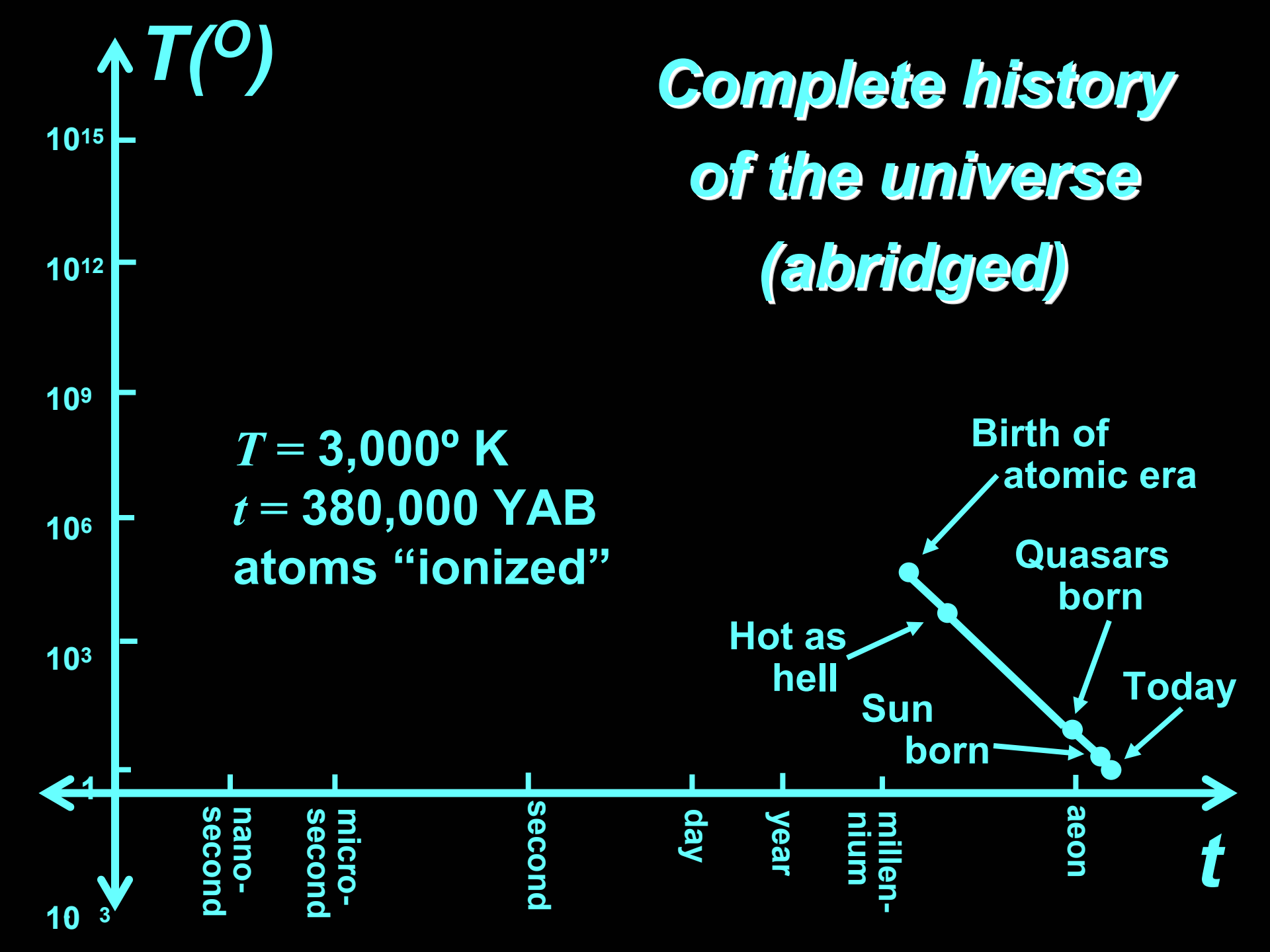
Gravitational redshift



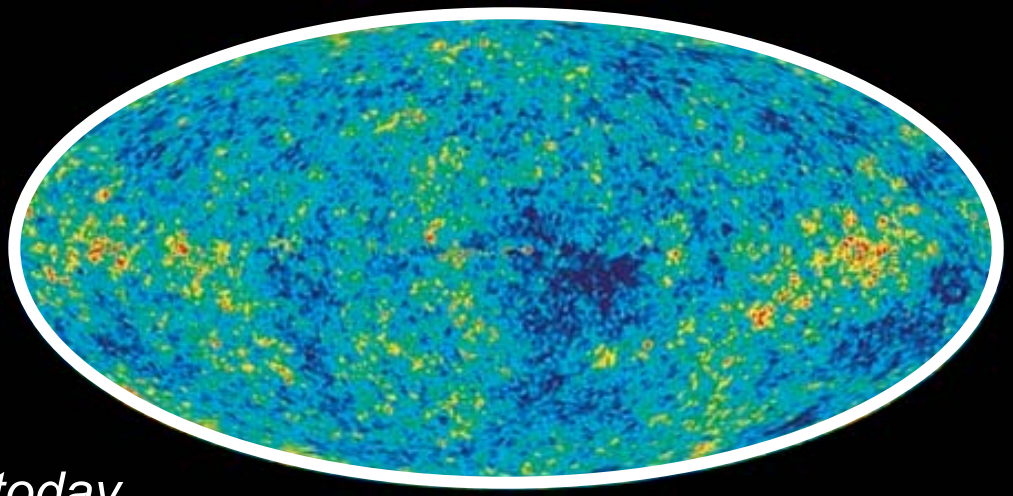
Expanding universe cools:

- Today T=3K
- Yesterday was hotter!
- Tomorrow will be colder!


Possible future of the universe
Today
Sun Burns Out
Hell Freezes Over
Cubs win Series
Universe Ends
14-billion years
18-billion years
hundred-billion years
thousand-billion years
billion-billion years
t

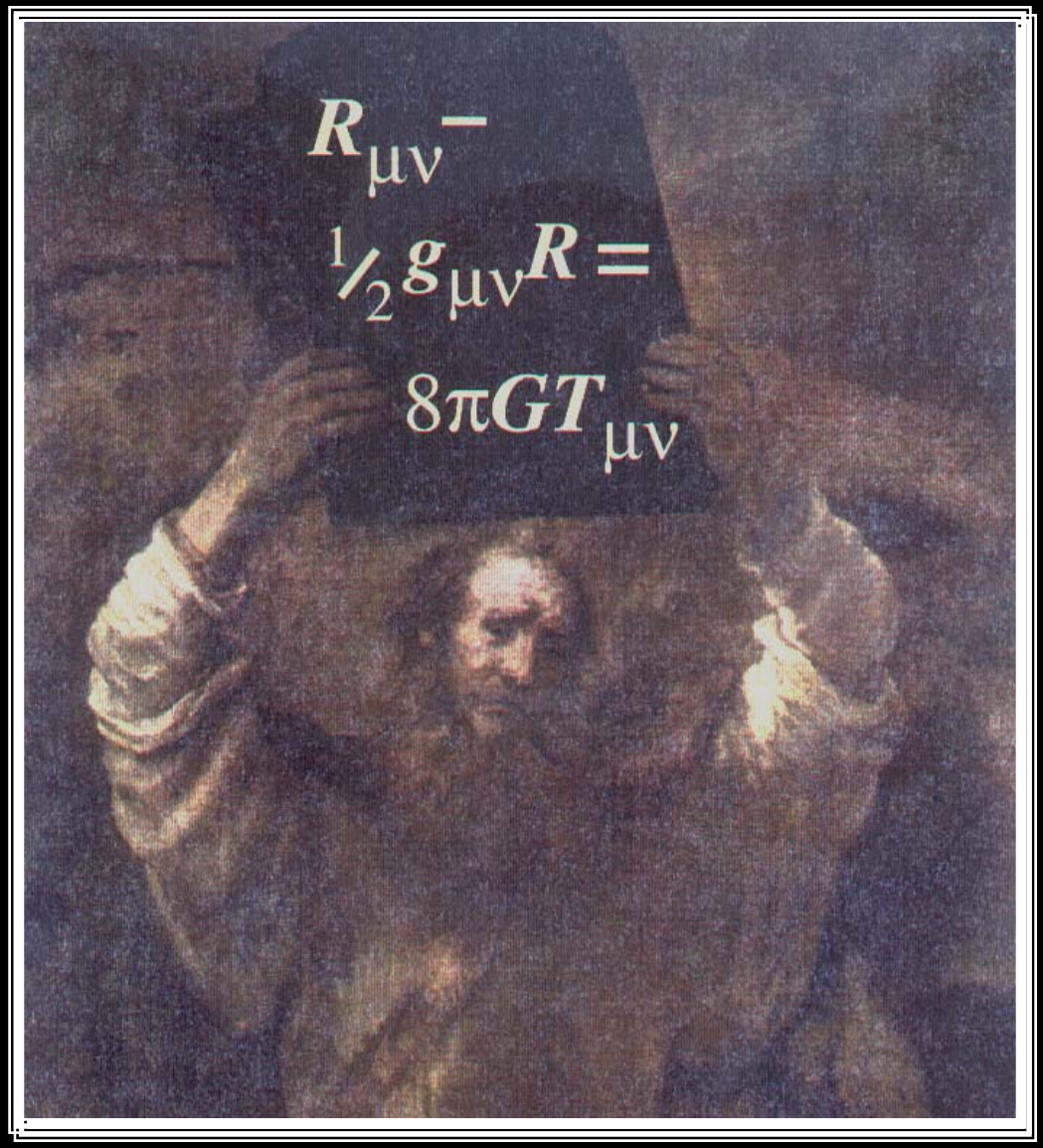

T(°)
Complete history of the universe (abridged)
10^15
10^12
10^9
10^6
10^3
1
10^-3
T = 3,000° K
t = 380,000 YAB
atoms "ionized"
Birth of atomic era
Quasars born
Hot as hell
Sun born
Today
nano-second
micro-second
second
day
year
millen-nium
aeon
t

Looking out in space is Looking back in time.

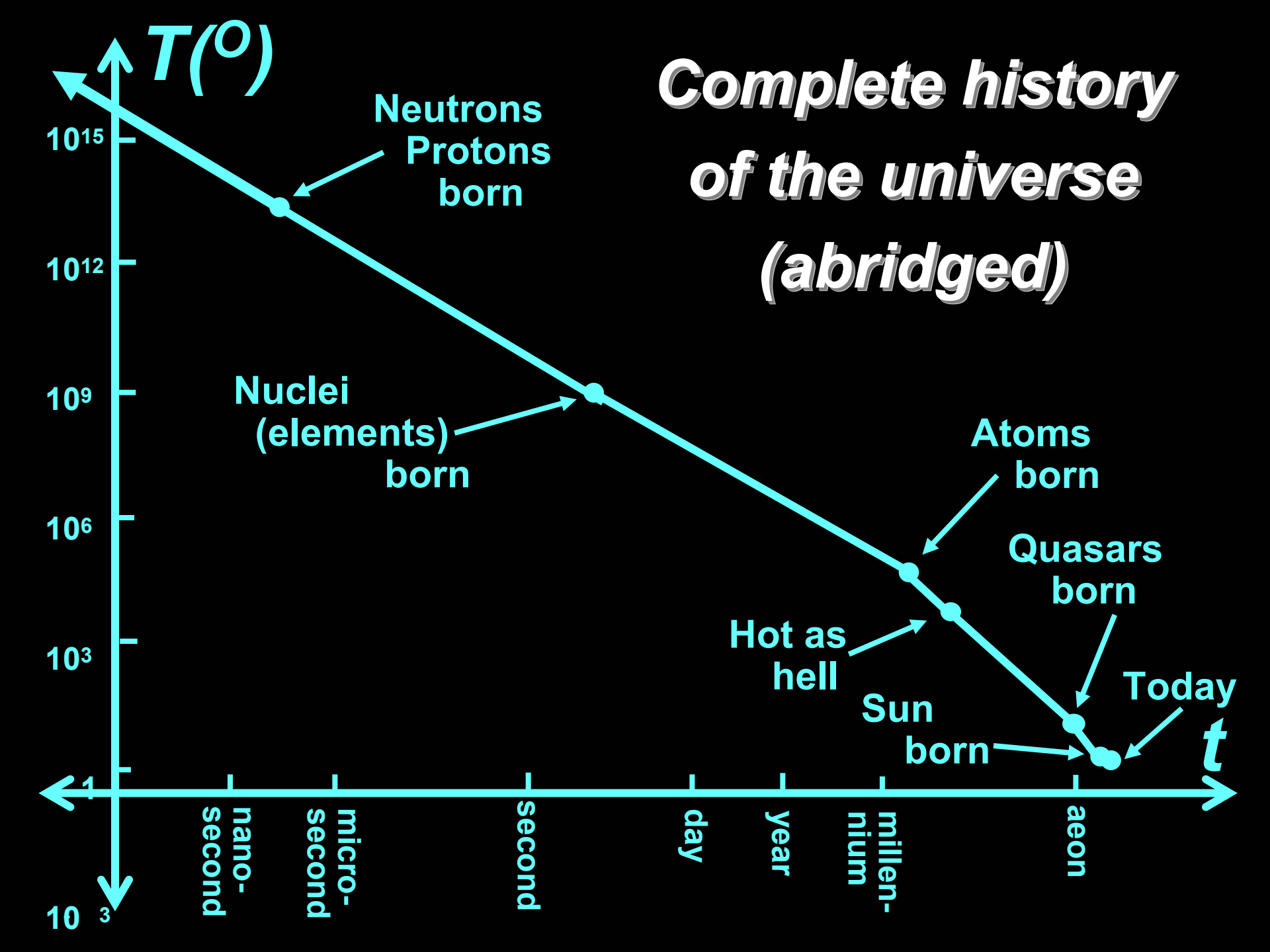


CBR: a snapshot of the universe 380,000 AB

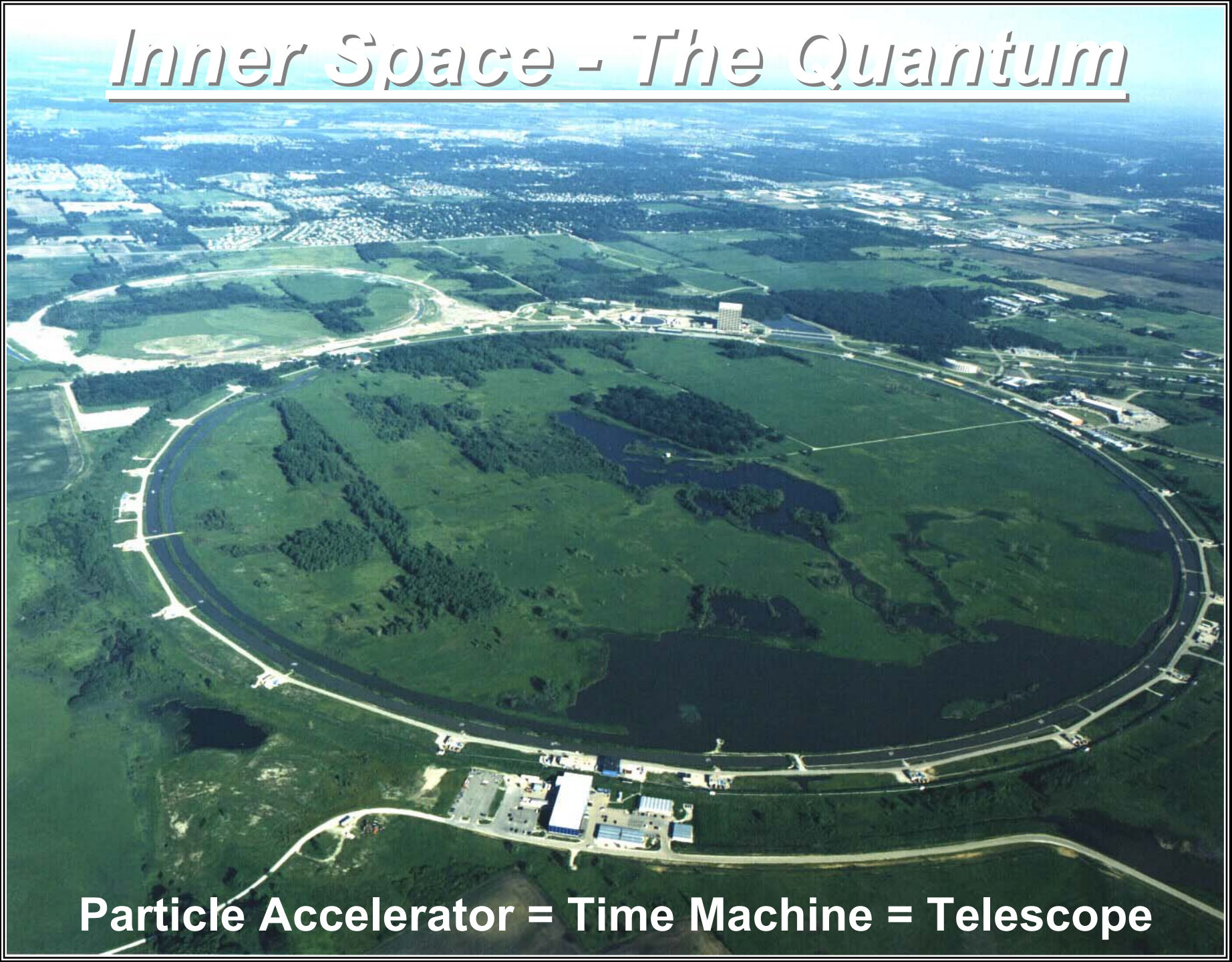
Modern laws of Genesis



(10 nonlinear partial differential equations)


T(°)
Complete history of the universe (abridged)
Neutrons Protons born
Nuclei (elements) born
Atoms born
Quasars born
Hot as hell
Sun born
Today
t
10^15
10^12
10^9
10^6
10^3
1
10^-3
nano-second
micro-second
second
day
year
millen-nium
aeon

Inner Space - The Quantum



Particle Accelerator = Time Machine = Telescope


Fermilabs
Primordial
SOUP

Primordial soup

0.000 000 000 004 seconds AB

3,000,000,000,000,000°

CONDENSED

in one can } 50 Earth masses in matter
50 Earth masses in antimatter
\+ extra mountain of matter

HOT

per serving } 10 billion years of total energy output of sun

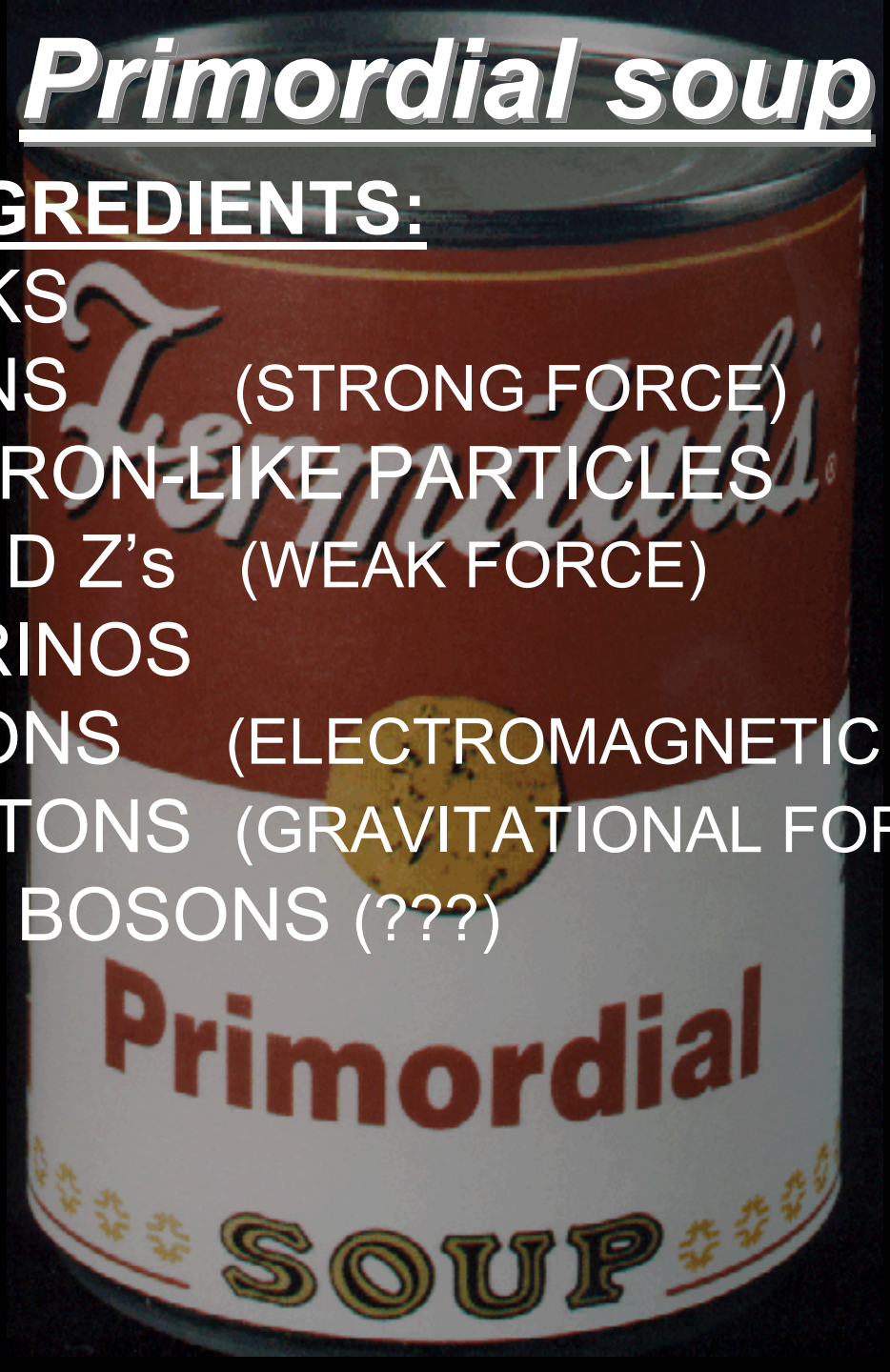
INGREDIENTS

in every spoonful } every type of elementary particle

Primordial soup

KNOWN INGREDIENTS:

56% QUARKS
16% GLUONS (STRONG FORCE)
9% ELECTRON-LIKE PARTICLES
9% W's AND Z's (WEAK FORCE)
5% NEUTRINOS
2% PHOTONS (ELECTROMAGNETIC FORCE)
2% GRAVITONS (GRAVITATIONAL FORCE)
1% HIGGS BOSONS (???)



Primordial soup

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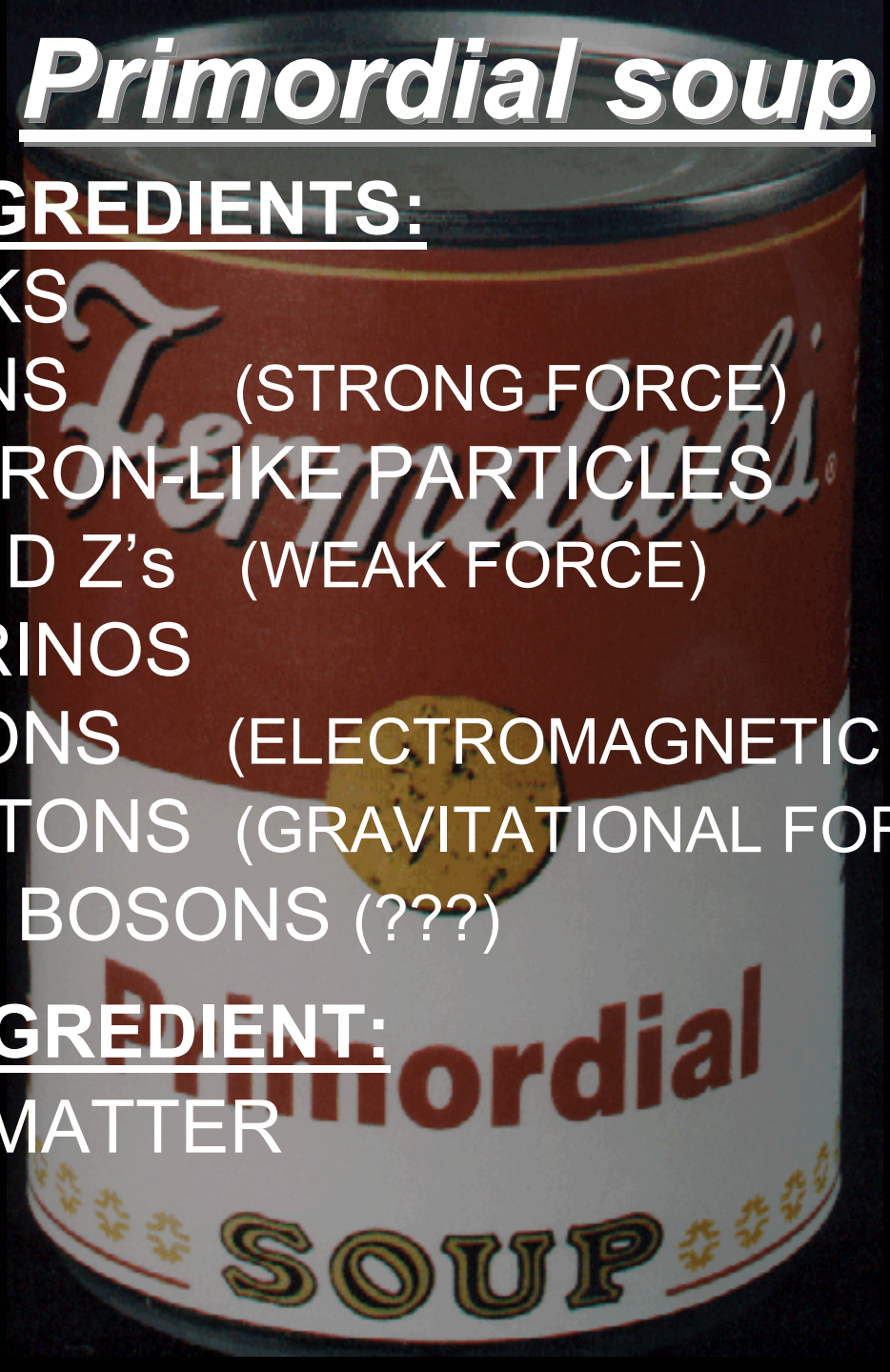
1% HIGGS BOSONS (???)

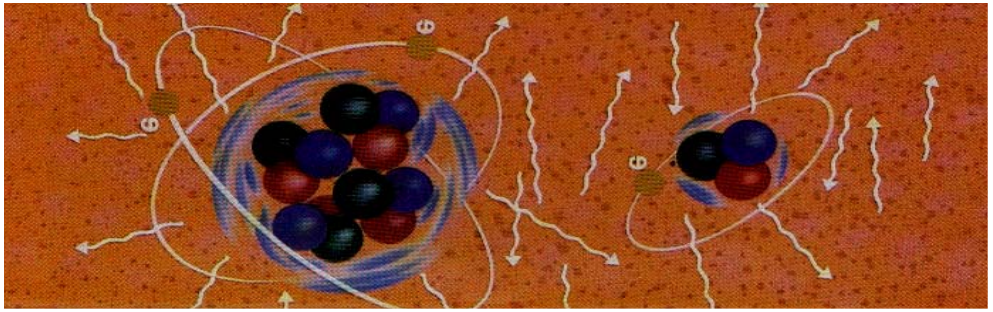
SECRET INGREDIENT:

DARK MATTER



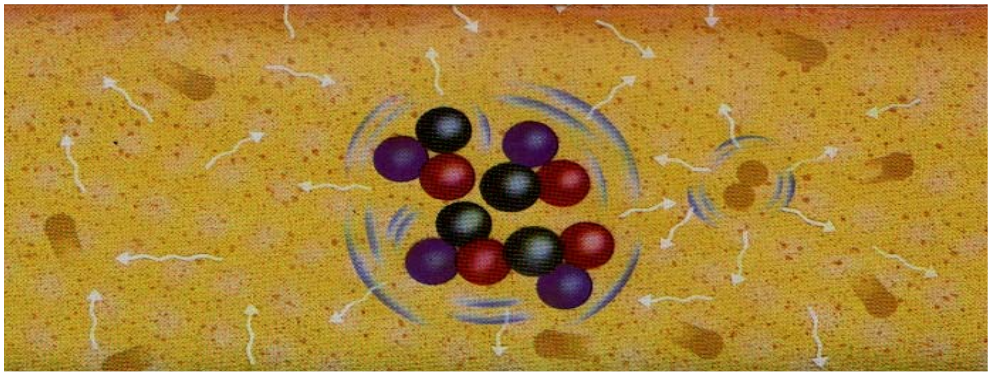
380,000 years

atoms form



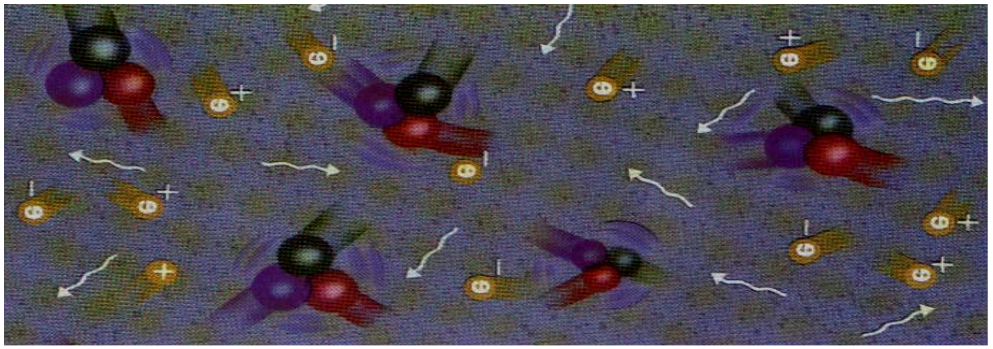
3 minutes

nuclei form



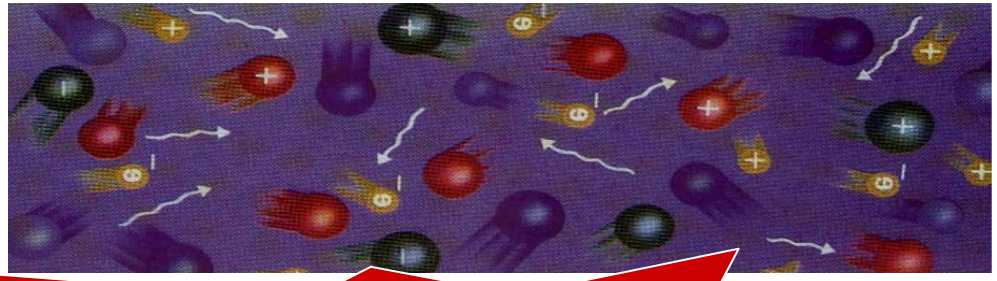
1-micro second

neutrons protons form



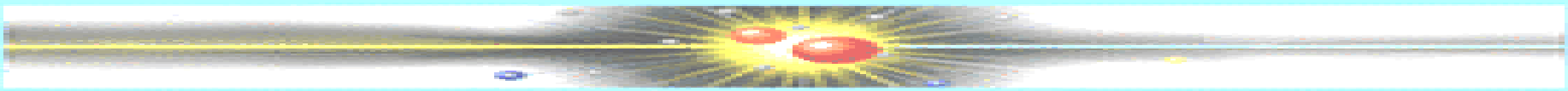
4-pico seconds

primordial soup



BANG!

EVERYTHING IN THE UNIVERSE



MICROWAVE RADIATION
SUPERCLUSTERS OF GALAXIES
CLUSTERS OF GALAXIES
STARS
PLANETS
PEOPLE
POODLES
PIGEONS
PETUNIAS
POND SCUM
KARL ROVE

FROM THE PRIMORDIAL SOUP!